

## BACKGROUND

Light propagating within an optical fiber undergoes chromatic dispersion which causes the light to be delayed within the optical fiber. The specific amount of dispersion that light undergoes varies depending upon the wavelength of the light. The manner in which an optical fiber causes light to undergo chromatic dispersion is typically characterized by two parameters: (1) the dispersion at one specific wavelength, and (2) the dispersion slope. The dispersion slope indicates the extent to which dispersion varies as a function of wavelength.

The dispersion slope of an optical fiber can significantly limit the usable bandwidth for a wavelength-division multiplex (WDM) system, which uses multiple information channels each having their own wavelength of light. Each information channel can accumulate its own amount of dispersion of the transmission link length. For example, in a WDM system having 10 Gb/s data-rate information channels, the information channels can accumulate a large amount of dispersion (e.g., more than  $\forall$  3000 ps/nm) over long transmission distances, such as transoceanic transmission distances (e.g., 7000-10,000 km). When the accumulated

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FIG. 2 illustrates accumulated dispersion as a function of transmission distance for the optical sublink shown in FIG. 1.

FIG. 3 illustrates the Q-factor (in dB) as a function of the link-span average dispersion (in ps/nm-km), for the optical link shown in FIG. 1.

FIG. 4 illustrates an optical sublink, according to an embodiment of the present invention.

FIG. 5 illustrates a graph of the accumulated dispersion (in ps/nm) as a function of distance (in km) for three wavelengths for the optical sublink shown in FIG. 4.

FIG. 6 illustrates a graph of the accumulated dispersion (in ps/nm) as a function of wavelength (in nm) for the optical sublink shown in FIG. 4.

#### **DETAILED DESCRIPTION**

An apparatus comprises an optical sublink including a operationally coupled optical fiber segments. The optical fiber segments are from a first optical fiber type, a second optical fiber type and a third optical fiber type. The first optical fiber type has a positive dispersion and a positive dispersion slope. The second optical fiber type has a negative dispersion and a negative dispersion slope. The third optical fiber type has one from the group of (1) a positive dispersion and a negative dispersion slope, and (2) a negative dispersion and a positive dispersion slope.

The term "optical fiber segments" is used herein to include portions of optical fibers where each optical fiber portion has its own optical and/or physical characteristics, such as dispersion, dispersion slope, effective cross-sectional area and/or length. The optical fiber segments can be operationally coupled to define a longer "optical sublink"; multiple optical sublinks can be coupled together to define an optical link. For example, two types of optical fiber segments can be alternately coupled to define an optical sublink. The optical sublink can include optical devices (e.g., optical repeaters or branching units) or optical components (e.g., coupling devices such as lens) between two optical fiber segments. The optical

sublink can be, for example, a portion of an optical communication system between the transmitter and the receiver.

The term "link spans" is used herein to include subsets of the optical link. For example, link spans can be portions of the optical link between two optical repeaters.

Optical fibers having opposite sign dispersions and opposite sign dispersion slopes are becoming commercially available. These optical fibers having appropriate lengths can be alternatingly coupled to form link spans of an optical sublink. FIG. 1 illustrates a portion of an optical link (i.e., an optical sublink) configured of optical fibers having opposite sign dispersion and opposite sign dispersion slope, in accordance with a one-level dispersion management (OLDM) scheme. In this particular example, the lengths of the optical fibers have similar lengths (although in other optical links, the optical fibers can have different lengths but similar relative dispersion slopes, as discussed below). As shown in FIG. 1, fiber 100 includes amplifiers 110, 120, 130, and fiber segments 140, 150, 160 and 170. Fiber segments 140 and 160 can be of the same first type having a dispersion,  $D_1$ , and having a length,  $L_1$ . Fiber segments 150 and 170 can be of the same second type having a dispersion,  $D_2$ , and having a length,  $L_2$ . In this example, a link span can be defined as fiber segments having the first and second fiber types (for example, fiber segments 140 and 150).

The first fiber type can have, for example, a dispersion,  $D_1$ , of 16.9 ps/nm-km; a dispersion slope,  $D_1'$ , of 0.06 ps/nm<sup>2</sup>-km; and an effective area of 75  $\mu\text{m}^2$ . Such a type of optical fiber is commercially available as "single-mode fiber (SMF)". The SMF fiber is produced by several fiber manufacturers including Corning and Lucent Technologies. The relative dispersion slope of the first fiber type equals the ratio of the first-fiber-type dispersion slope and dispersion,  $D_1'/D_1$ .

The second fiber type can have, for example, a dispersion,  $D_2$ , of -17.0 ps/nm-km; a dispersion slope,  $D_2'$ , of -0.06 ps/nm<sup>2</sup>-km; and an effective area of 35  $\mu\text{m}^2$ . Such a type of optical fiber has been designated commercially as "1x inverse-dispersion fiber (1x-IDF)". Another example of an optical fiber having a negative

$$D = \text{avg} \frac{D_1 L_1 + D_2 L_2}{L_1 + L_2}$$
$$D'_{\text{avg}} = \frac{D'_1 L_1 + D'_2 L_2}{L_1 + L_2}$$

It has been recognized, however, that such a configuration has a less than optimal performance. FIG. 3 illustrates the Q-factor (in dB) as a function of the link-span average dispersion (in ps/nm-km), for the optical link shown in FIG. 1. As FIG. 3 illustrates, when the magnitude of the link-span average dispersion is around

zero, the Q-factor (and thus the system performance) is reduced. This is due to cross-phase modulation. As the magnitude of the link-span average dispersion is increased from zero, the Q-factor increases to a maximum before decreasing again due to intersymbol interference from too much dispersion accumulation.

Consequently, the inventors have recognized that dispersion maps using dispersion-slope-compensating optical fibers should be designed so that the magnitude of the average dispersion accumulated over a link span is substantially greater than zero while the overall optical sublink has an accumulated dispersion less than a dispersion tolerance limit. In other words, regardless of whether the average dispersion accumulated over a given link span has a negative value or a positive value, the absolute value of the average dispersion accumulated over a given link should be substantially greater than zero so that the cross-phase modulation is reduced to an acceptable level. Said another way, the dispersion map can be designed, for example, so that the magnitude of the accumulated dispersion at a particular link span is substantially greater than zero until the last link span corrects for the accumulated dispersion thereby reducing the accumulated dispersion at the end of the optical sublink to a desired value.

Moreover, the design of dispersion maps using dispersion-slope-compensating optical fibers are such that the dispersion slope for the overall optical sublinks is compensated while also compensating for the accumulated dispersion. This, however, presents a difficulty in that an optical sublink combining two optical fiber types yields a zero dispersion slope at a specific (generally non-zero) dispersion determined by the properties of the optical fibers. Therefore, the inventors have recognized that it is desirable to be able to specify independently the dispersion and the dispersion slope of a dispersion map so that, for example, the end of an optical sublink can have a desired dispersion (for example, a dispersion less than a dispersion tolerance) and a dispersion slope substantially equal to zero. The term "dispersion slope substantially equal to zero" can include a relatively small dispersion slope resulting in accumulated dispersions for multiple wavelengths with

variance within an acceptable tolerance (e.g., a variance of 0.2 ps/km for a 30 nm range of wavelengths for an optical sublink having a 540 km length).

A dispersion map can be designed where the dispersion and the dispersion slope are independently selected through the combination of at least three types of optical fibers having complementary characteristics. By using a combination of these fiber types, two degrees of freedom can be obtained so that both the dispersion and the dispersion slope can be specified for a dispersion map. Note that this is one more degree of freedom than is the case where two optical fiber types have complementary characteristics (e.g., where one optical fiber type has a positive dispersion and a positive dispersion slope, and the other optical fiber type has a negative dispersion and a negative dispersion slope).

FIG. 4 illustrates an optical sublink, 200 that includes optical amplifiers 210, 211, 212, 213 and 214. Optical sublink 200 also includes fiber segments 220, 230, 240, 250, 260, 270 and 280. Optical sublink is configured such that the following components are connected in series: amplifier 210, fiber segment 220, fiber segment 230 and amplifier 211; amplifier 212, fiber segment 240, fiber segment 250, amplifier 213, fiber segment 260, fiber segment 270, fiber segment 280 and amplifier 214. Note that for optical sublink 200, amplifier 211 and amplifier 212 are coupled together through a series of link spans including fiber segments and amplifiers not shown in FIG. 4. For example, the optical sublink 200 can have ten fiber spans between amplifiers 210 and 213 and an eleventh fiber span between amplifiers 213 and 214.

Fiber segments 220, 240 and 260 can be a first type of optical fiber (such as, for example, SMF (single-mode fiber discussed above)). Fiber segments 230, 250 and 280 can be a second type of optical fiber (such as, for example, 1x-IDF or 2x-IDF discussed above). Fiber segment 270 can be a third type of optical fiber (such as, for example, dispersion-shifted fiber which has a dispersion of -2 ps/nm-km, a dispersion slope of about 0.08 to 0.05 ps/nm/km/nm and an effective area of 55  $\mu\text{m}^2$ ; such a type of optical fiber is commercially available and manufactured by, for example, Lucent Technologies and Corning). Note that the particular order of fiber

As just discussed above, the optical sublink 200 can have, for example, ten fiber spans between amplifiers 210 and 213 and an eleventh fiber span between amplifiers 213 and 214. In such an embodiment, the fiber spans between amplifiers 210 and 213 can each include a pair of fiber segments having the first fiber type (e.g., SMF) and the second fiber type (e.g., IDF). In this embodiment, the length of fiber segments within the link spans between amplifier 210 and 213 can be, for example, 25 km. Said another way, the fiber segments 220, 230 through 240 and 250 can each have a length of, for example, 25 km. The length of fiber segments 260, 270 and 280 can be, for example, 12.5 km, 1 km and 25 km, respectively.

Generally speaking, the first optical fiber type can have, for example, a positive dispersion and a positive dispersion slope. The second optical fiber type can have, for example, a negative dispersion and a negative dispersion slope. The third optical fiber type can have, for example, either (1) a positive dispersion and a negative dispersion slope, and (2) a negative dispersion and a positive dispersion slope. By using a combination of three optical fiber types with complementary characteristics, two degrees of freedom can be obtained so that both the dispersion and the dispersion slope can be specified for a dispersion map.

FIG. 5 illustrates a graph of the accumulated dispersion (in ps/nm) as a function of distance (in km) for three exemplary wavelengths 1526 nm, 1547.5 nm and 1569 nm. for the optical sublink shown in FIG. 4. As FIG. 5 shows, the dispersion map for the optical sublink shown in FIG. 4 can such that the dispersion for each fiber span can have an increasing accumulated dispersion until the last fiber span 300 (i.e., the portion of optical sublink 200 that includes amplifier 213, fiber segment 260, fiber segment 270, fiber segment 280 and amplifier 214) corrects for the dispersion and the dispersion slope.

In other words, as FIG. 5 illustrates, the accumulated dispersion for each wavelength differs for the various fiber spans of the optical sublink 200 until the end



In addition, although the dispersion map discussed herein as an example had an increasing accumulated dispersion until the last link span within the optical

sublink, other types of dispersion maps are possible. For example, in another embodiment, the dispersion map can have a decreasing accumulated dispersion until the last link span within the optical sublink at which point the last link span can be selected so that the accumulated dispersion returns towards zero and the dispersion slope is compensated (thereby resulting in multiple wavelengths having substantially equal accumulated dispersion).

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